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Authors' contributions

This work was carried out in collaboration between all authors. Author AM carried out the steric calculations, including methodology consideration, data selection, data processing, and comparisons. He performed the result analysis and drafted the manuscript. Author OV participated in GRACE data processing and in analysing the impact of the steric circulation on the Lake dynamics. He also participated in the design, coordination of the study and helped to draft the manuscript. Author LM participated in altimetry data processing and accuracy assessment. He also helped in literature searches. Author SH helped in the analysis of results and improving manuscript structure. All authors read and approved the final manuscript.

Article Information

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ABSTRACT

This article investigated the principal reason for water circulations in the Caspian Sea. Unlike other inland water bodies, and similar to the open seas, the Caspian Sea shows regular water circulations which are not explained by the wind. The Steric contribution of water level fluctuations was studied in this article by two approaches: one from remote sensing and climatology data, and

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the other, from space altimetry and gravimetry data. The approaches are fundamentally different: the first approach directly observes and measures the steric fluctuations, while, the second approach estimates the steric fluctuations by analysing their causing factors such as water temperature and salinity. Analysis of over 13 years data showed that estimations from these two approaches are consistent. Based on the results, the Steric Sea Level (SSL) included a seasonal cycle of about 8.5 cm and a seasonal topography of 4 and 7 cm in winter and summer respectively. The seasonal water circulations observed in the lake was consistent with the geostrophic response to estimated steric topography. Moreover, the results demonstrated that the seasonal water surface topography is the reason for water circulation in the Caspian Sea.

1. INTRODUCTION

Located in northwest Asia and with a surface area of 371,000 km^2, the Caspian Sea is the world's most substantial inland water body, with 40 to 44% of the total lacustrine waters of the world. The annual inflow to the Caspian Sea comes from more than 130 rivers. The Volga River contributes the most, whereas the only natural outgoing flux is evaporation from the lake surface. Sea level fluctuations of the order of a few meters have been recorded over the last centuries; which are mostly addressed to natural climate variabilities [1-4]. The lake also shows seasonal fluctuations caused by the change in the lake water balance inducing variations in the total water content [5]. Beside seasonal changes of input water, a steric effect also can cause seasonal fluctuations. The steric level changes due to the variations of water density. As well, the effect of wind blowing over the lake could deform its surface locally.

Whereas the global Caspian Sea level has been the topic of several studies [6,7,8], the water surface topography of the lake has not been investigated to date. The lake itself is only sparsely monitored through in-situ technique, which makes its evolution and dynamics challenging to study. On the other hand, to investigate such a vast lake, remote sensing observations are essential. In particular, since 1992, a series of satellite altimetry missions, beginning with the TOPEX/Poseidon satellite have directly measured sea surface heights. Satellite altimetry measurements allow continuous and homogeneous monitoring of the water surface topography.

With the GRACE (Gravity Recovery And Climate Experience) mission, starting in 2002, it is now possible to quantify the spatio-temporal change of total water storage and its associated water level. This allows determining the part of sea level resulting from the change of the total mass content. Space altimetry, on the other hand, measures the apparent water level change [9], which indicates integrated mass and volume effects. Therefore, with combining GRACE and altimetry estimations, the part of the sea level change associated with water density variations can be separated from the region related to changes in the total water content, as previously studied [8,10]. Water temperature measurements are used globally to estimate water density variations and general circulations within the oceans [11]. Beside water temperature, water salinity data was used in a limited number of studies [12]. Together temperature and salinity can control the water volume variations. However, the effect of temperature is stronger than salinity [13] due to the stronger seasonal variation of temperature. The salinity effect includes only about 10 %t of the total steric effect in the oceans [14]. This portion should be smaller in the case of the Caspian Sea because its salt content is about one-third of the oceans.

The steric effect could have a role in seasonal and inter-annual scales. A portion of the global sea level rise during the last decades refers to water expansion as the results of water temperature increments. Water thermal expansion includes about one-third of total sea level rise [15]. This rate reaches up to about 0.7 to 1 mm per year [16]. However, seasonal variations of steric effect cause global water circulations that have an essential role in global climate and marine biosphere. Oceanic water circulations have been associated with steric effects. Inland water bodies usually do not experience water circulations. Due to its largeness, however, several works [17-21] reported a cyclonic surface water circulation in deep central and southern regions.

Nonetheless, the physical explanation for those currents remains to be found. The dynamics of

the Caspian Sea is not very well known, nor well understood. This article aims to investigate the presence of a steric effect in the Caspian Sea and see how does the steric impact controls the lake water circulation, considering its amplitude and spatio-temporal variations.

2. DATA

To investigate water density, water temperature, and salinity data are required. Considering that the total input of salt via the rivers is negligible, 3D models for temperature and salinity are reconstructed utilising remotely sensed Sea Surface Temperature (SST), and temperature/salinity climatology profiles. The NOAA National Ocean Data Center distributes the SST data. These data are reproduced through an optimum interpolation of Advanced Very High Resolution Radiometer (AVHRR), [22]. Temperature and salinity profiles were obtained from in-situ sounding by World Ocean Atlas 2009 -WOA- [23,24]. To compute the total water mass changes, three different solutions of GRACE GRGS were processed. The data used in both approaches are summarised in Table 1.

3. METHODOLOGY

Two different approaches constructed the time series of steric fluctuation; 1) computing the water density variations, and 2) subtracting the water level deduced from the GRACE data to the water level obtained from space altimetry.

3.1 Steric Sea Level from SST and Climatology Data

The sea water is well stratified in nature. The topmost layer is mixed, and a thin homogeneous layer and a thermocline layer is situated beneath the mixed layer. The later layer shows a strong vertical temperature gradient, below which only negligible water density variations occur. Based on the Atlas data of temperature and salinity [23,24], the mixed layer is thinner than 10 m in the Caspian Sea. Indeed, the temperature and salinity gradients over the first ten meters are more significant than the typical value for a mixed layer. Boehrer and Schultze, [25] estimated the thermocline depth for several lakes in various geographic areas and showed a robust correlation between the mean lake depth and the depth of its thermocline. The mean thermocline depth of the Caspian Sea is not specified yet. However, Peeters et al. [26] estimated a thermocline depth of about 90 m and 160 m, in

the deep central basin and the southern basin of the lake respectively. Jamshidi [27] observed a 40 m deep thermocline in the south of Caspian Sea, in an area closed to the coast with 100 m average depth.

Therefore, the study expects that the mean thermocline boundary of the Caspian Sea stands between 110 and 150 m. This limit is consistent with the estimations from Boehrer & Schultze, [28] for some other lakes around the world. To model mean water density variations above the thermocline depth, the Atlas data are only appropriate available data for the region of study. Climatology profiles from the Atlas are classically provided at 24 standard levels in the oceans (down to 1500 m). However, for the Caspian Sea, only levels 0, 10, 20 and 30 m are available. Then the World Ocean Atlas data linearly extrapolated down to the thermocline depth; as only the order of magnitude is required, this crude method was adapted for the present study. By combining SST with WOA models, the temporally and spatially varying bulk temperatures were computed.

With about 210 m of average depth over the Caspian Sea, one can neglect the compressibility of water column [29]. The water density time variations between the surface and thermocline depth were calculated from temperature and salinity using equations from McCutcheon et al. [30], and integrated vertically to obtain the steric water level fluctuations (Equation 1). The estimated steric fluctuations for thermocline lower boundary at 110m and 150m are shown in Fig. 1.

$$\rho_w = f(T_w, S_w), \; SSL_{SST/SSS} = \int_0^T \Delta\rho_w \qquad (1)$$

3.2 SSL from Space Altimetry and Gravimetry Data

The stabilised GRACE models from the solutions processed by GRGS and JPL were used in this approach. The main steps of this solution are the followings:

1. Subtraction of the mean gravity fields.
2. Calculation of the density and Equivalent Water Height on a grid of 0.5-by-0.5 degree.
3. Masking the lake extent to isolate the signal of the lake.
4. Averaging grids over the lake surface, to estimate the equivalent water height anomalies.

5. Estimating the leakage in/out effects and correcting the estimations of equivalent water height.

After removing the inter-annual variations from the water level time series, the steric sea level change is estimated as follow:

$$SSL_{\text{alti/gravi}} = \left(SLA_{\text{altimetry}} - SLA_{\text{GRACE}}\right) - \left(SLA_{\text{nonsteric}}\right) \qquad (2)$$

The time series show a robust seasonal cycle affected by strong irregular fluctuations. This study focused on the seasonal cycle, which is isolated by computing a composite annual period. The curve of 8.3 cm amplitude results in the minimum residual of remaining random fluctuations (Fig. 2).

3.3 Accuracy Assessment

In the literature, an uncertainty of about 1 to 1.7 °K is observed for the NOAA derived SST over the open seas [31,32,33,34,35]. However, an uncertainty level of 1.83°C in SST data was found for the Caspian Sea. The standard errors for the climatologic means of WOA were produced by the distributor [36], which showed that the maximum standard errors in all depths in the Caspian Sea were 1.5°C and 0.3 kg/m^3 for temperature and salinity respectively. The results showed that the sea steric variation was 1.95 mm per 0.1 g/kg for the salinity change; and 2.95 mm and 3.75 mm per °C for the temperature change in winter and summer respectively. Thus:

$$E_{\text{T\_summer}} = 2 * 3.75 = 7.5\ mm \quad , \quad E_{\text{T\_winter}} = 2 * 2.95 = 5.9\ mm, \quad E_{\text{Salinity}} = 2 * 1.95 = 3.9\ mm \quad (3)$$

Therefore, the overall error of the steric sea level derived from the SST/SSL was estimated as follow:

$$E_{\text{steric}_{\text{SST}}} = \sqrt{(7.5)^2 + (3.9)^2} = 8.4\ mm$$

Error of steric sea level in summer $\qquad (4)$

$$E_{\text{steric}_{\text{SST}}} = \sqrt{(5.9)^2 + (3.9)^2} = 7.1\ mm$$

Error of steric sea level in winter (5)

Table 1. List of the datasets used

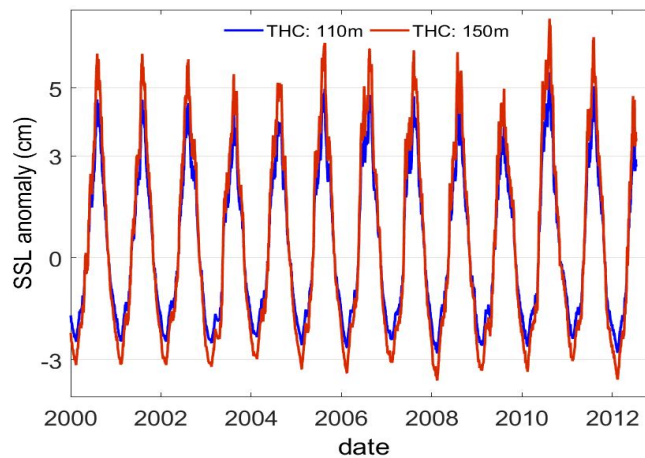| Parameter	Dimension	Dataset		Period	Temporal resolution	Spatial resolution
Temperature	Horizontal	NOAA SST		2000 - 2012	Daily	0.25° - 0.25°
	Vertical	WOA 2009		Static	Monthly Mean	1° - 1°
Salinity	Horizontal	WOA 2009		Static	Monthly Mean	1° - 1°
	Vertical	WOA 2009		Static	Monthly Mean	1° - 1°
Water Mass Anomaly	Horizontal	GRACE	GRGS RL-2	2002 - 2012	10 day	400 km
			GRGS RL-3	2003 - 2012	Monthly	250 km
			JPL RL-5	2003 - 2015	Monthly	200 km

Fig. 1. Seasonal Steric fluctuations of the Caspian Sea level, calculated for the estimated minimum (THC=110) and maximum (THC=150) thermocline depths
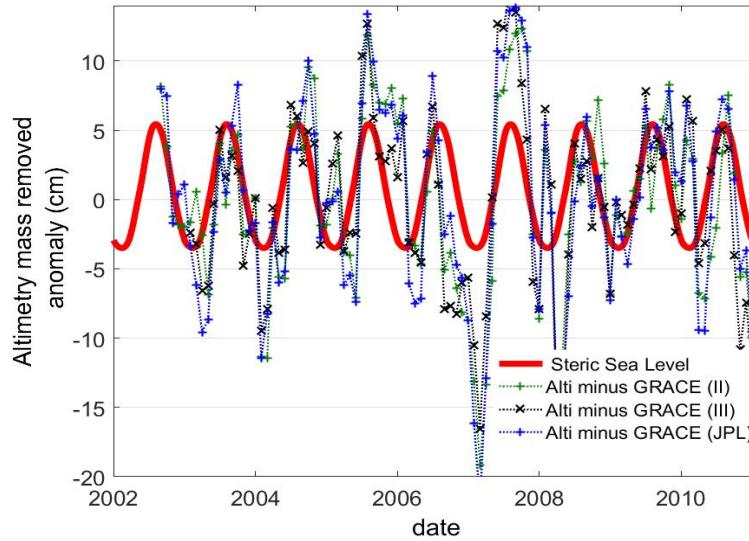
Fig. 2. Altimetry minus GRACE: all signal (dotted lines), fitted seasonal signal (red line)

Having a correlation coefficient of 0.66, water temperature and salinity showed a dependency. Thus, the true error is half the covariance between two kinds of error. Note that, to this point, there was not enough information to make an accurate assessment for the thermocline depth. For this reason, two shallow and deep limits for the lake thermocline were introduced.

The formal mapping errors were provided by AVISO Live Access Server (LAS) for Sea Level Anomalies. Based on these maps, the error in the Caspian Sea was 3.22 cm on average. Previous studies reported a precision range from 2 to 3.5 cm in water thickness estimated from

GRACE data [7,37-40]. The errors in GRACE estimations decreased at higher latitudes [7], including the Caspian Sea region. By considering the dispersion of measurements, the investigation of uncertainty showed that the uncertainties were 3.16 and 2.84 cm for GRACE RL02 and RL03 time series respectively. Overall uncertainty of steric sea level derived from altimetry/GRACE is as follow:

$$E_{steric\,\text{Alti/GRACE}} = \sqrt{(E_{Alti})^2 + (E_{GRACE})^2} \ , then \qquad (6)$$

$$E_{steric\,\text{Alti/G02}} = \sqrt{(3.22)^2 + (3.16)^2} = 4.5\,cm \qquad ,$$

$$E_{steric\,\text{Alti/G03}} = \sqrt{(3.22)^2 + (2.84)^2} = 4.3\,cm \quad (7)$$
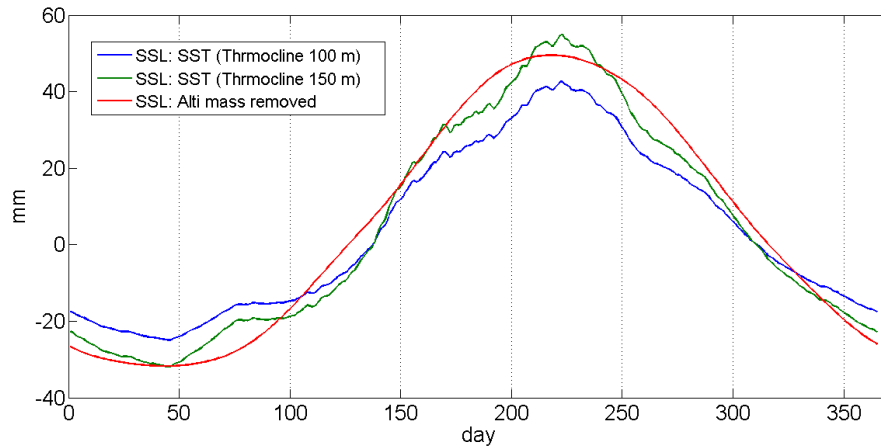

Fig. 3. Mean seasonal SSL derive from 1) SST data (calculated for two thermocline depths of 110 m and 150 m), and 2) altimetry/GRACE

The mean seasonal cycle of SSL was estimated by fitting over nine years of data. The final uncertainty was thus $\sqrt{9}$ times smaller, due to averaging, then:

$$E_{steric_{Alti/GRACE}} = E_m/\sqrt{N_m} = 4.4/\sqrt{9} = 1.46\ cm \quad (8)$$

Where, E_m is the measurement error, and N_m is the number of measurements. Without considering the thermocline precision, the SST-based SSL has higher accuracy than the Altimetry and GRACE-based one.

3.4 Comparison of the Two Mean SSL Estimations

SST steric estimation is expected to be more precise and better sampled than the altimetry and GRACE one, but strongly depends on the unknown thermocline bottom depth. Consequently, it was decided to use the SST-based estimated and fix the thermocline lower boundary utilising the altimetry and GRACE estimate results. To reconcile the amplitude of the seasonal cycle from the two methods, the study found an average depth of thermocline limit at 145 m. By applying this thermocline limit, the magnitude of seasonal SSL was about 8.5 cm (Fig. 3).

4. IMPACTS ON THE LAKE CIRCULATION

4.1 Lake Topography Variations

Based on the altimetry measurements, which has also been confirmed by the monitoring of the shorelines using MODIS images [5], the lake topography exhibits a seasonal signal, as illustrated in Fig. 4.

The sea surface topography determined from altimetry was corrected for the contribution from steric sea level variations (Fig. 5 A). The remaining topography features, appearing mostly in the northern part of the lake, resulted from river discharges and winds. These topographies occur at the high frequencies (Fig. 5 B). The high frequencies topography of the sea surface filtered; the resulted map (Fig. 5 C) shows that no deep-shallow topography remains; implicating that, the steric associated topography was appropriately removed.

4.2 Impact of the Steric Circulation on the Lake Dynamics

The non-steric contribution to the sea level did not present seasonal lake-scale topography. Thus the seasonal water circulation in the lake was induced by the steric component [41]. Based on the steric elevation, the induced geostrophic current pattern was estimated using the classical geostrophic equations:

$$u_g = -\frac{g}{f}\frac{\partial Z}{\partial y}$$
$$v_g = \frac{g}{f}\frac{\partial Z}{\partial x}$$

Where u_g and v_g are the geostrophic zonal (along x) and meridional (along y) velocities, g is the gravity acceleration, f is the Coriolis factor, and Z is the water elevation.
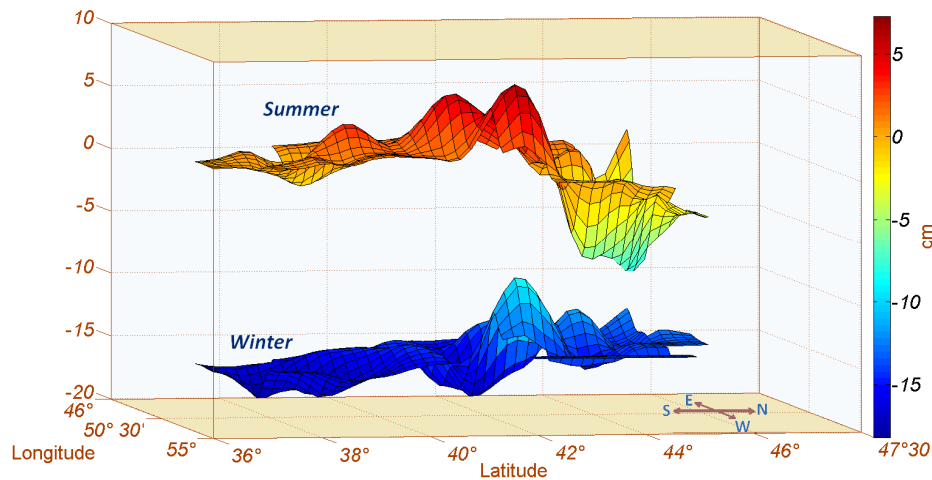

Fig. 4. Water level fluctuation in the lake, derived from the multi-mission dataset (averages over 19 years)
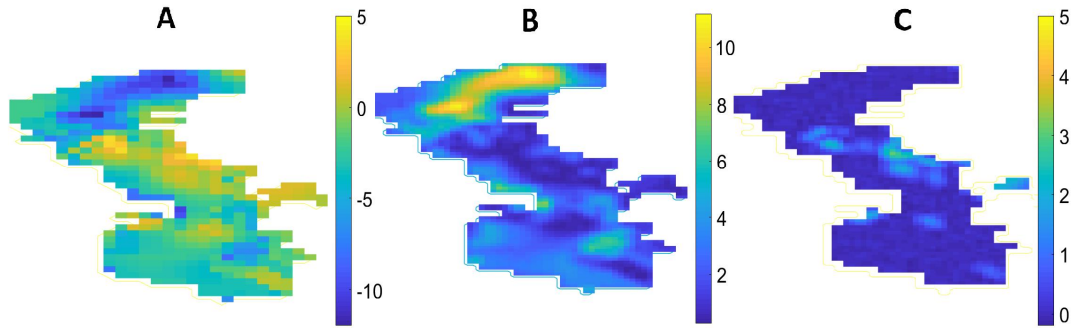
6

Fig. 5. Removing high-frequency topography using a Fast Fourier Transform: A is water level fluctuations in summer (altimetry steric removed), B shows high-frequency topographies, and C is water level fluctuations after eliminating high-frequency topographies

Because of the Earth rotation, in the northern hemisphere, the currents tend to turn right, and a cyclonic water circulation always forms around a valley on sea surface due to the Coriolis effect [41]. The computed circulation pattern agrees with the observed cyclonic currents in winters (Fig. 6); when the central and southern parts of the sea stand get lower than other regions, causing a valley like form. These two parts are split by the sea bottom topography, which forms the two separate cyclones in the water circulation. Ibrayev et al. [21] have limited the cyclonic gyres to December–January; and they have modelled south, south-westward surface current during February–July. This model,

especially in the southern part, is similar to an anti-cyclonic circulation, as expected from the results. In the North-West, the current patterns are not consistent with what would be expected from the steric topography, but the flow of the Volga rivers, which enter the sea in that area, contributes to the current dynamics in that part of the Lake. In addition, Ibrayev et al. [21] have assimilated the minimum sea surface topography in July (7.5 cm) and the maximum in December (15 cm). Their estimation for July is consistent with the present result, but the December's estimated topography is four times larger than the estimation in winter. It is neither consistent with the altimetry records.
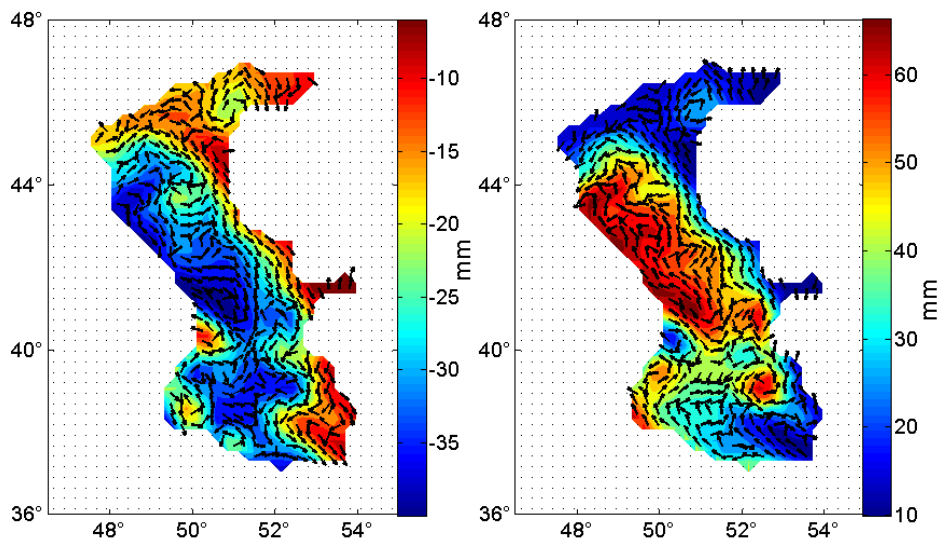

Fig. 6. Map of the direction of the geostrophic currents associated with the SSL in summer (right) and winter (left). Note that the size of the arrow is normalised and should not be interpreted

5. CONCLUSIONS

Among inland water bodies, the Caspian Sea has a particular specification, as it shows regular water circulations. Studying the fluctuation level of the Caspian Sea is challenging due to the lack of in-situ data. Moreover, a large annual river discharge into the lake makes it challenging to measure steric fluctuations and separate it from the total annual cycle. In this paper, considering these conditions, the lake steric fluctuations and surface topography were investigated using two differently applicable approaches. The first approach was observing steric effect by integration of satellite gravimetry and altimetry. However, the second approach utilised physical water parameters (temperature and salinity) to estimate the steric fluctuations. The strong point of the applied approaches was that they studied one phenomenon in both perspectives, one approach discussed that how the steric effect in the lake was expected to be, and the other one, reported the actual situation of steric effect in the lake.

Due to the low spatial resolution of GRACE observations, the first approach did not allow to see the local steric topography, whereas this topography was clearly discovered in the second approach. The steric topography is 4 and 7 cm in winter and summer respectively. This topography is essential to explain the seasonal water circulations which were not previously justified. The computed geostrophic currents associated with the steric topography allowed us to explain the observed circulations of the Caspian Sea.

A direct comparison of the two approaches on the average SSL signal showed a fair agreement, which gives us the confidence to interpret the steric induced topography. It is worth mentioning that the low resolution of some data probably causes most of the irregularity in the computed water topography. Notably, a higher resolution bathymetry map would improve the features because the bathymetric separation between central and southern regions of the lake are not correctly reflected in the 0.5° by 0.5° depth map. Temperature plays a dominant role in steric effect effects. It explains more than 90 % of steric fluctuations. Therefore temperature profiles to a greater depth would allow for a better thermocline determination, and consequently, allow for a more precise steric topography computation. Inter-comparison of two approaches permitted balancing a thermocline depth of about 145 m in the Caspian Sea, which

are consistently comparable to the other lakes. Nevertheless, the agreement of the estimated current field resulting from the steric topography with what has been observed in the Caspian Sea dynamics confirms that the present approach has adequately retrieved the major features of the signal.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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